Life-cycle climate impacts of peat fuel: calculation methods and methodological challenges

**Juha Grönroos · Jyri Seppälä · Sirkka Koskela ·
Antti Kilpeläinen · Pekka Leskinen · Anne Holma ·
Juha-Pekka Tuovinen · Jukka Turunen · Saara Lind ·
Marja Maljanen · Pertti J. Martikainen**

Abstract

Purpose There has been lively debate, especially in Finland and Sweden, on the climate impacts of peat fuel. Previous studies of peat fuel's life-cycle climate impacts were controversial in their interpretation. The aim of this paper is conclusive examination of the issues of LCA methodology, derived from critical review of previous studies and recalculation based on the latest knowledge of greenhouse gas balances related to peat fuel's utilisation and the radiative forcing impacts of greenhouse gases.

J. Grönroos (✉) · J. Seppälä · S. Koskela
Finnish Environment Institute,
Production and Consumption Centre,
P.O. Box140, 00251 Helsinki, Finland
e-mail: juha.gronroos@ymparisto.fi

A. Kilpeläinen · P. Leskinen · A. Holma
Finnish Environment Institute,
Production and Consumption Centre,
P.O. Box 111, 80101 Joensuu, Finland

J.-P. Tuovinen
Finnish Meteorological Institute, Climate Change Research,
P.O. Box 503, 00101 Helsinki, Finland

J. Turunen
Geological Survey of Finland, Kuopio unit,
P.O. Box 1237, 70211 Kuopio, Finland

S. Lind · M. Maljanen · P. J. Martikainen
University of Eastern Finland, Faculty of Science and Forestry,
Department of Environmental Science,
Biogeochemistry Research Group,
P.O. Box 1627, 70211 Kuopio, Finland

Methods The most recent findings on emissions and the gas fluxes between soil, vegetation and atmosphere were used in calculation of the life-cycle climate impacts of the various peat fuel utilisation chains by means of LCA methodology. In the main, the calculation methods and rules were the same as in the previous studies, with the aim being to distinguish the impact of peat fuel's utilisation from that of the natural or semi-natural situation. A dynamic method was employed for assessing changes in radiative forcing. The results of alternative peat fuel utilisation chains were compared to the corresponding result for coal.

Results There are many steps in peat fuel LCA, where different assumptions lead to different outcomes. Determining the functional unit, reference situations and system boundaries, as well as the emission calculation methods, is important from this point of view. Determination of the initial reference situation emerged as one of the critical points in the calculations. Time scale can strongly affect the final outcomes in a study where effects of long-term land-use change are considered.

Conclusions Each peatland area is unique. The higher the greenhouse gas emissions in the initial reference situation, the greater is the climate impact of the area and the more suitable the area is for peat extraction. The study showed that more greenhouse gas flux measurements are needed, for better assessment of the climate impacts of different potential peat extraction sites. Climate change mitigation requires quick actions, and uncertainties related to emissions are higher for longer time spans. Therefore, it can be concluded that a perspective spanning more than 100 years is inappropriate in peat fuel's life-cycle climate impact assessments.

Keywords Climate change · Energy · Land use · Life-cycle assessment · Peat fuel

1 Introduction

Peat is formed through the accumulation of carbon in the vegetation of marshy areas over the course of centuries. In pristine peatlands, peat is inhibited from decaying by acidic and anaerobic conditions. Global peat reserves are vast; 2 % of the earth's territory is covered by peatlands (WEC 2007). The most peat-rich areas are North America, Northern Asia, Northern and Central Europe and Indonesia. The biggest peat producers are Ireland, Finland, Belarus, Russia, Sweden and Ukraine. Peat is utilised mostly in agriculture and energy production. The importance of peat fuel at the national level is greatest in Finland and Ireland, where peat provides for approximately 5–7 % of primary energy consumption. The corresponding values for Estonia and Sweden are 1.9 and 0.7 %, respectively (Paappanen et al. 2006). Outside Europe, energy use of peat is minimal.

There has been some debate surrounding peat's fuel classification. For example, in Finland peat is classified as slowly renewable biomass. The guidelines of the Intergovernmental Panel on Climate Change (IPCC) place peat in a category of its own, between renewable and fossil fuels (IPCC 2006). Internationally, peat is considered a fossil fuel (according to the European Union Emission Trading Scheme, the statistics of OECD/IEA and Eurostat). Concern over climate change, and the EU's targets for reduction of greenhouse gases (GHGs) have brought peat energy under scrutiny. In recent years, especially in Finland and Sweden, there has been lively debate on peat fuel's climate impacts.

Several life-cycle assessment (LCA) studies of peat fuel utilisation chains (which we term PFUCs) demonstrate that peat energy has climate impacts almost equal to those of utilisation of coal or other fossil fuels in energy production (Hagberg and Holmgren 2008; Hillebrand 1993; Kirkinen et al. 2007; Savolainen et al. 1994; Uppenberg et al. 2001). Some of the results of these studies were controversial in their interpretation of the climate impact of peat fuel as compared to fossil fuels such as coal. Seppälä et al. (2010) clarified the debate and provided a better basis for Finnish energy policy decision-making by summarising the latest scientific knowledge of the climate impacts of peat energy on the basis of LCA methodology and by critically assessing previous peat fuel LCA studies in light of the ISO 14040 and ISO 14044 standards (ISO 2006a, b). They too concluded the climate impacts of peat energy and coal energy to be equal. However, variation in the results does exist, depending on the calculation methods used.

The aim of this paper is to cast light on the substantive issues of the LCA methodology used in the most recent peat energy study (Seppälä et al. 2010) and discuss their relevance in analogous life-cycle studies wherein land-use issues and time-span aspects must be considered. In this paper, we focus only on the climate impacts of the PFUCs.

Other environmental aspects, such as negative impacts on biodiversity or surface waters are not considered.

In Section 2, we describe the materials and methods of the LCA case study of peat fuel. Section 3 focuses on the main results of the case study. In Section 4, the key issues and the most influential factors that emerged in our study, affecting the final results and causing diversity in land-use-based LCA applications—i.e. the role of initial data, methodological choices, and calculation rules are discussed, and some general notes about uncertainties related to the calculation methods and data are addressed. The final section presents our main conclusions.

2 Materials and methods

2.1 Utilisation chains and the functional unit

Peat can be harvested from a variety of peatlands. Three alternative peatlands were chosen to represent the initial reference situations (situations before peat harvesting): pristine mire (PM), forestry-drained peatland (FDP) and cultivated peatland (CP). Restoration or afforestation was considered as a final stage in the utilisation chains. Mire drainage, peat extraction and peat combustion were other phases of the life cycle in the chains (Fig. 1). Peat extraction starts after vegetation stripping and ditching (years 1–5). In our study, drainage phase was excluded from the system boundaries as in other studies its impact has been negligible.

The extraction typically takes 20 years, and peat combustion occurs during this period. After the peat extraction phase, after-treatment takes place, in the form of afforestation or restoration.

The functional unit (a quantified performance of a product system—see ISO 2006a) was defined to be 1 PJ of peat fuel combusted in a power plant over 20 years. The energy content of peatland was assumed to be 3,384 MJm^{-2} (Kirkinen et al. 2007). This means that 1 PJ of peat fuel energy requires a peat extraction area of 30 ha. The extraction and combustion phases last only 20 years. Usually, the entire time span of peat fuel LCAs is 100 or 300 years, including decades or centuries of after-treatment. However, because the period of extraction is so short, the significance
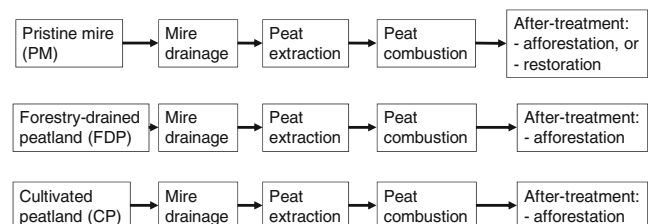

Fig. 1 The life cycle phases of the three alternative peat fuel utilisation chains

of the after-treatment may be great, depending on the changes in the net emissions. This will be discussed in more detail in the following sections.

2.2 Inventory and impact assessment

In the inventory phase, emission data were collated for the most important GHGs: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The key parameters used in our peat fuel case study are presented in Appendix 1 of the Electronic supplementary material (ESM). Data on fossil-fuel-based emissions were gathered for the use of work machines and peat transportation services (Uppenberg et al. 2001). The emissions from stockpiles (Nykänen et al. 1996; Sundh et al. 2000) were also included in the inventory. A central source of GHGs is the peat combustion process. The emission factors used for combustion were based on work by Statistics Finland (2005) and Vesterinen (2003). However, the most challenging part of the inventory is the peatland itself, which is a dynamic biological system. The temporal variability of both CO_2 emission/uptake rates and CH_4 emission rates is large, and the spatial variability is also significant, both between peatland types and within a certain type (such as pristine fens) (e.g. Saarnio et al. 2007). The most recent measurement data (Aurela et al. 2004, 2007, 2009; Saarnio et al. 2007; von Arnold et al. 2005) were used for estimating the long-term net ecosystem CO_2 exchange rates for both pristine fens and bogs.

The effect of afforestation can be divided into two parts: emissions from the soil caused by the decomposition of the residual peat and, second, sequestration of carbon (C) caused by forest growth on the peatlands before and after peat extraction. Furthermore, forest growth causes an input of C to the soil through aboveground and belowground forest litter (litter accumulation). Some of this litter will decompose. For assessment of net GHG emission change in the peatland area, the C fluxes due to litter production and the decomposition of organic matter in the soil should be known. The development of carbon stock in the retired peat production area's soil due to afforestation was estimated by means of the Yasso07 model (Tuomi et al. 2009).

We express the climate impact of GHG emissions as both Global Warming Potential (GWP) and radiative forcing (RF). For the GWP, we use the CO_2 equivalency for a 100-year time horizon and the GWP100 factors of the IPCC (Solomon et al. 2007). RF is a measure of the change in Earth's radiation balance and in this study represents the net changes in atmospheric GHG concentrations that result from the activities considered in the peat fuel LCA. No further effects related to changes in land use, such as changes in the reflectivity of the vegetation surface (albedo), were considered. RF was calculated through a modified version (Lohila et al. 2010) of the REFUGE model (Korhonen et al. 1993;

Monni et al. 2003). This model enables dynamic modelling of the atmospheric GHG increments and the related RF as a function of the emission dynamics along the peat fuel utilisation chain, taking into account the different residence times and radiative efficiencies of the GHGs considered, as well as the projected development in their background concentrations. The parameter values used in the calculation model correspond to those recommended by the IPCC (Solomon et al. 2007).

2.3 Calculation rules for peat utilisation chains

A starting point for the comparison of different alternative PFUCs was to calculate the changes in GHG balances in the peat fuel production area over time. For this reason, it was necessary to define a *reference scenario* for each PFUC, describing the non-utilisation situation that corresponds to the average pre-extraction conditions in the peatland area. Emissions from this phase are considered to be avoided in the *utilisation scenario*, which covers all activities in the peat fuel utilisation chain. Therefore, the equation used for these calculations was (Savolainen et al. 1994)

$$I = I_u - I_r \tag{1}$$

where I is the net climate impact (expressed via radiative forcing calculations) caused by the peat utilisation chain, I_u refers to the climate effects of the peat utilisation scenario and I_r is the climate impact caused by the reference scenario.

Taking into account all the above-mentioned aspects of the chain, we developed our general calculation rules. For instance, that for FDP—afforestation was

$$I = I_u - I_r = IPE_{EA} + IPE_{HT} + IPC + IAF_{DRP}$$
$$+ IAF_{CT} + IAF_{CAS} - (IR_{NS} + IR_{CT}) \tag{2}$$

where the net climate impact (I) is derived from peat extraction in the extraction area (PE_{EA}), harvesting machinery and transportation in the extraction area (PE_{WT}), peat combustion (PC), decomposition of residual peat in the afforestation phase (AF_{DRP}), carbon sequestration in trees in the afforestation phase (AF_{CT}), carbon accumulation in the soil in the afforestation phase (AF_{CAS}), net emissions from the soil in the initial reference situation (R_{NS}) and carbon sequestration in trees in the initial reference situation (R_{CT}).

Average annual forest growth (aboveground and belowground) values were assumed in the reference situation for FDP but not for PM and CP. However, afforestation with forest growth was assumed to be an after-treatment option in all of the utilisation chains (see Fig. 1). In the after-treatment of FDP, the average forest growth was assumed to be equal to the values in the reference situation, or higher. Therefore, forest growth and, thus, C sequestration in trees and C accumulation in the soil in the after-treatment phase could

be fully attributed to peat fuel in the net climate impact calculations of PM and CP chains. In the case of FDP the increased forest growth and resultant changes in C fluxes were associated with peat fuel.

2.4 Fossil fuel as a reference fuel

The coal utilisation chain was used as a reference to which the peat fuel utilisation chain was compared in climate impact terms. In the coal utilisation chain, all phases of the life cycle —coal's mining, transport and processing, and combustion— were taken into account in accordance with the life-cycle approach. In contrast, GHG emission credits (avoided emissions) from by-products such as fly ash, bottom ash and gypsum were not taken into account. All activities outside peat extraction areas after peat combustion were omitted also from the peat fuel utilisation chain. Thus, the results of LCAs for peat and coal were rendered comparable. The approach selected because the emission credits do not play an important role in the GHG emissions from the coal-energy system (e.g. Seppälä et al. 2005). As in the case of peat fuel, to make the systems comparable, also in the coal fuel utilisation chain the 1 PJ of fuel is combusted within 20 years.

3 Results

According to our results, two PFUCs (PM and FDP) have greater climate impacts than reference fuel coal does (Fig. 2). CP has smaller impacts, because of the higher avoided emissions in the initial situation.

The results showed that the climate impacts of PFUCs are mostly caused by CO_2 released by peat combustion (Fig. 3a and b). Because the emissions from combustion are dominant, it is important that those emission values be as reliable
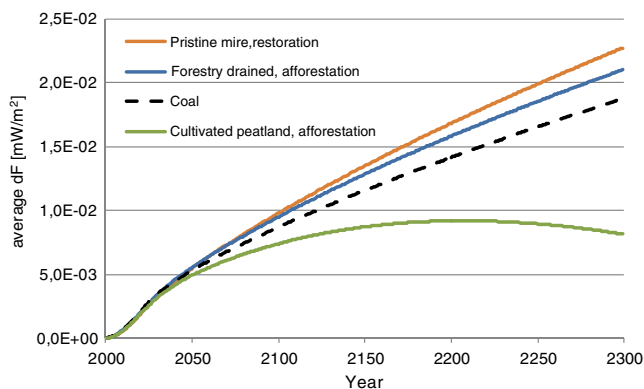

Fig. 2 The cumulative radiative forcing effect ($mW m^{-2} PJ^{-1}$) caused by peat fuel utilisation chains and by the coal reference system. Peat's harvesting and combustion as well as utilisation of coal take place during the years 2000–2019, and the after-treatment of peatland covers the years 2020–2300. The 5-year drainage stage before peat extraction was not considered

as possible. For this purpose, the official emission factors were used. In the Finnish GHG inventory system (Statistics Finland 2005), emission factors of 105.9 and 94.6 $g MJ^{-1}$ are used, for peat and coal, respectively. Additionally, during combustion, other GHGs are released. For peat, the significance of both methane and nitrous oxide is low, as shown by the CO_2 equivalents (conversion via GWP100 factors, Solomon et al. 2007) of CH_4 and N_2O emissions (0.0085 g CH_4 MJ^{-1} = 0.2 g CO_2 equiv. MJ^{-1}; 0.0128 g N_2O MJ^{-1} = 3.8 g CO_2 equiv. MJ^{-1}). There are further important life-cycle phases and factors contributing to the total climate impacts of PFUCs, although in the case of FDP they have little relevance, with approximately 15 % of the total CO_2-equivalent emissions of the system (see Fig. 3a). They originate mainly from the after-treatment phase. The emissions from the peat harvesting area are of minor importance, and emissions from transport and harvesting equipment are in practice insignificant. When the emissions from the reference situation are subtracted from those of the peat utilisation chain, the role of the peat combustion phase becomes even more dominant (see Fig. 3b).

Emissions from the soil in different parts of the peat extraction chain may significantly affect the final results, as may carbon balance data and calculation methods. In this context, we consider only some of the challenges in C balance calculations, related to peat's decomposition and changes in vegetation growth.

System boundaries may also affect the final results. This is mostly related to the question of whether the area surrounding the actual extraction site should be included in the assessment and, if included, what the size of that area is in relation to the actual harvesting area and how the GHG balances of that area have changed on account of the peat extraction. For the peat fuel LCA calculations, one must choose initial and final reference situations, system boundaries and the time perspective. These factors are discussed in more detail in the following sections.

4 Discussion

4.1 Definition of the functional unit

Where different fuels or different PFUCs are compared in LCAs, use of a certain amount of energy that is the same for all systems studied is a suitable functional unit. When different PFUCs are studied, a certain area of peatlands could be utilised as a functional unit. This is also appropriate when the aim is to compare the impact of different land-use alternatives whose final products are different, such as peat fuel's utilisation and forestry.

In the case where the functional unit is a certain amount of fuel energy, as in our study (1 PJ of peat fuel), the specific

Fig. 3 **a** Life-cycle GHG emissions (tonnes CO_2 equiv. PJ^{-1}) of FDP over 100 and 300 years for the reference situation and for the case in which peat is utilised in energy production with afforestation as an after-treatment option. Peat harvesting and combustion takes place for a 20-year period and the afforestation phase for an 80- or 280-year period. The emissions of the reference situation (for 100 or 300 years) *have not been subtracted* from the emissions of the peat fuel utilisation chain. GHG emissions were converted into CO_2 equivalents using the IPCC GWP100 equivalency factors (Solomon et al. 2007). **b** Life-cycle GHG emissions (tonnes CO_2 equiv. PJ^{-1}) of FDP over 100 and 300 years for different peat utilisation phases, when the emissions of the reference situation *have been subtracted* from the specific emissions of each of the utilisation phase (net emissions). Peat harvesting and combustion takes place for a 20-year period and the afforestation phase for an 80- or 280-year period. GHG emissions were converted into CO_2 equivalents using the IPCC GWP100 equivalency factors (Solomon et al. 2007)
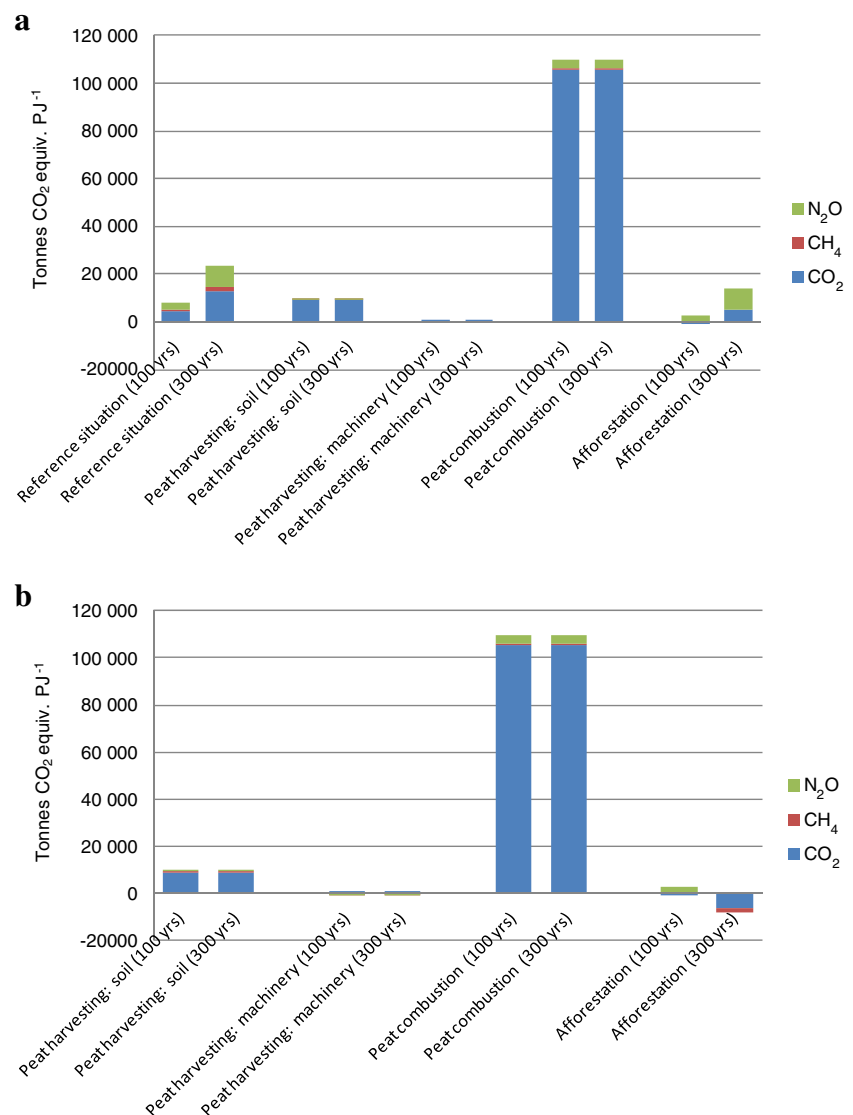
emissions per unit of energy produced depend on the acreage of peatland that is required to produce that amount of energy, and the harvesting time period. In our study, average values (30 ha, 20 years) were used. In practice, both of these factors can vary significantly on a case-specific basis.

4.2 Definition of the system boundaries

In LCA studies, definition of the system boundaries typically plays an important role in the final results. As was shown above, the climate impact of peat fuel is composed of peat extraction, transportation and combustion phases, and emissions due to land-use changes. Peatland drainage and clearing is also included in some studies but its impact is proved to be negligible.

Information on the size of the surrounding area—i.e. the area around the actual peat extraction site that is affected by drainage—is very uncertain. It is obvious that the size varies

significantly with the case at hand. Additionally, the emissions from that area are not known.

Inclusion of the surrounding area may have a considerable impact on the results (Holmgren et al. 2006). If peat extraction leads to a state with lower emissions of GHGs in the surrounding area, the climate impact of peat fuel is lower than in a case where the surrounding area is not considered. The greater the emission reduction due to peat extraction, the greater its contribution in climate impact terms.

In the study of Nilsson and Nilsson (2004), the area affected by drainage was assumed to be the same as the actual extraction area, while in the study of Kirkinen et al. (2007) the surrounding area was not considered. This is one of the main reasons for the differences in results between individual peat fuel LCA studies. Especially in the climate impact calculations for CP, inclusion of the surrounding area is highly questionable, because there is no evidence that the peat extraction would affect that area and because the

surrounding area is used for agriculture. In the most recent Swedish study (Hagberg and Holmgren 2008), the assumptions regarding the surrounding area were changed; for PM, the surrounding area affected by the drainage was assumed to be half the size of the extraction area, but for FDPs and drained CPs the surrounding area was omitted.

In our study, the assumptions used in the study of Hagberg and Holmgren (ibid.) were accepted as the best currently available assumptions for the effects on the surrounding area. Because forestry-drained peatlands and cultivated peatlands are already affected by earlier drainage activities, the peat harvesting does not affect the emissions from surrounding areas in these cases.

In addition to changes in land use usually having direct effects on emissions from the soil, indirect impacts due to changes in related production systems may be seen.

In our study, however, we did not consider indirect impacts arising from termination of wood production during the peat extraction phase, because we assumed that the impact would be small and because, at the same time, the growth of trees normally increases after the relatively short break in forestry. Furthermore, if this increased tree growth due to peat harvesting replaces fossil fuels, it can be questioned, whether it is correct to assign the emission credits from avoidance of fossil fuels to peat fuel? Another point is that if the stand is fertilised after the peat extraction phase, the increase in tree growth and emission credits due to fertilisation cannot be attributed to peat fuel. Additionally, we did not estimate the indirect impacts occurring when the production of agricultural products moves to another location. The reason was that it is highly unclear whether it would move and, if moved, what kind of site it would occupy.

4.3 Definition of the initial reference situation

In previous peat fuel LCA studies as well as in our research, the aim of the calculation procedure used was to quantify the changes in net GHG emissions that arise from utilisation of peat fuel. As was discussed above, taking land use into account necessitates determining the reference state of the peat extraction area—i.e. initial reference situation—for determining the emissions from that specific area were no peat harvesting to take place there. The aim is thus to quantify the difference in GHG emissions in a certain peat production area not only during but also before and after peat extraction. The state before peat extraction corresponds to the initial reference situation. The state after peat fuel production includes all states of the chosen peat area due to changes caused by human activities, from mire drainage to final reference situation.

In the net GHG emission approach (see Section 2.3), the CH_4 emissions from the initial reference situation of a PM are considered to be avoided emissions when production of peat fuel begins. The calculation method used follows LCA principles under which the aim is to assess the actual impact of a human activity on GHG emissions. However, the key question is how to determine the initial and final reference situations in the calculations. Especially in the case of CP but also for FDP, how the initial reference situation is determined may significantly affect the final results. The greater the GHG emissions from an initial reference situation are, the greater the benefits seen for peat fuel's utilisation.

However, the following question might be worth considering: is it right to use the previous human activity (and the emissions from it) as an initial reference situation, because the greater the emissions are from that activity, the higher the credits are for the next activity. In theory, the same question applies for FDP, because the area has already been drained and, so, the emissions from that area are affected by the previous human activity. One could argue that the forest draining has permanently changed the nature of the area and the emissions arising can be avoided only if the area is actively restored or, alternatively, if maintenance of the ditches is neglected, which, in the long run, will result in natural restoration of the area. This would take place over several decades, so also the changing reference emissions should be taken into account when the emissions from the peat fuel utilisation chain are calculated. However, if we view draining as permanent land-use change, use of forestry-drained peatland as an initial reference situation can be accepted. This principle has been applied in our study.

For CPs, the situation is different and more complicated because farming activities take place each year and emissions vary with the farming practices. Additionally, active farming produces agricultural products and the emissions will be attributed to those products. If we take an actively farmed area as the initial reference situation, we should note that a certain quantity of agricultural products has to be considered too. If, as was discussed in the previous section, peat harvesting is initiated in the area, also the production of agricultural products ends. This should be taken into account in the calculations through an assumption that the agricultural production moves to another area and the emissions from producing the same amount of agricultural products elsewhere should be included in the emissions of the peat fuel utilisation chain.

However, where the agricultural production would move is not obvious. The new area might be abandoned farmland or natural or semi-natural areas, such as forestry-drained peatlands, which would be cleared for agricultural purposes. Because the indirect land-use changes and emissions can only be guessed at, we did not apply the above-mentioned principle for this case. In Finland, CPs under active farming are significant sources of GHGs, especially CO_2 and N_2O. For this reason, it is recommended to avoid turning over these fields. Termination of active farming and leaving the area fallow is the simplest way to decrease GHG emissions from CPs. For cultivated peatlands with crop production, emissions of GHGs average 1,840 g CO_2

m^{-2} a^{-1}, 0.1 CH_4 gm^{-2} a^{-1} and 1.5 g N_2O m^{-2} a^{-1}, and the corresponding figures for abandoned cultivated peatlands are 1,180, −0.2 and 1.3 gm^{-2} a^{-1}, respectively (for data sources, see Appendix 1 of the ESM). To avoid assessing the very uncertain effects of indirect land-use changes and avoid using human activity as an initial reference situation (and because at present there is no acute need to keep all field areas in Finland under cultivation, enabling abatement of certain field areas), we decided to use abandoned cultivated peatland as an initial reference situation for the 'Cultivated peatland, afforestation' case. Besides this, we used actively cultivated organic cropland as a reference to see how an alternative reference situation affects the final result (see Seppälä et al. 2010); however, we believe that the results with the abandoned organic cropland scenario probably describe the final impacts of the energy-peat use of cultivated peatlands better.

4.4 Carbon dioxide exchange between atmosphere and biosphere

Peat harvesting changes GHG emissions and sequestration in peat production areas, which contributes to climate impacts (land-use effect). The routes of CO_2 are complex, as changes in forest growth have direct effects on carbon sequestration in trees but also on soil litter production, affecting the soil's C accumulation and consequent release rates (Fig. 4).

Carbon 'input' to the system occurs when C from the atmosphere is sequestered in the ecosystem by trees and other plants, forming carbon stocks. Carbon 'output' from the system occurs when these stocks (e.g. peat and litter) are oxidising—i.e. when organic matter is decomposing (heterotrophic soil respiration). The measurements of these fluxes of C that can be taken as a basis for climate impact calculations vary annually and seasonally, and they depend on site characteristics such as site fertility, soil conditions, the water table and the forest management practices used in
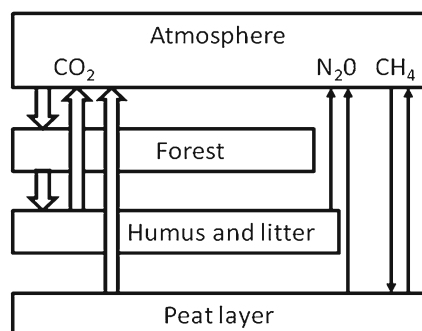

Fig. 4 Carbon dioxide emissions and sequestration between atmosphere and biosphere in the afforestation phase. Furthermore, nitrous oxide and methane fluxes between soil and atmosphere are marked in the figure. Most of the afforested peatlands are small methane sinks because oxidation of atmospheric CH_4 by soil methanotrophic bacteria is exceeding the production of CH_4 in soil by methanogens

both the reference situation and the after-treatment phase. In general, there are very few long-term datasets applicable for LCA calculations, especially where restoration and cutaway peat production areas are concerned. Also, existing data include only certain types of mires and their after-treatment options (Seppälä et al. 2010).

However, with the data utilised in our study, in the case where the reference situation is that of pristine mire, C input was greater than C output; i.e. the C balance (net carbon exchange) was negative because new peat was formed. In the case of FDP, decomposition takes place already in the reference situation. However, it may be enhanced with peat extraction, thus causing greater annual C emissions to the atmosphere than in the reference situation. Here the C balance is positive; that is, output is greater than input. After peat extraction, afforestation was the usual after-treatment option chosen, and when tree growth was assumed to increase because of the peat extraction, the C balance always improved in comparison to the reference situation.

Since the difference between the carbon exchange in the reference situation and utilisation situation matters in the climate impact calculations, great care must be taken in the choice of representative values for carbon input and output both in the initial reference and in after-treatment situations. The climate impact calculations are affected because the assumed change in carbon sequestration by trees after afforestation is linked to the utilisation of peat. If there is an increase in the accumulation of woody biomass—e.g. due to fertilising—the benefit (more sequestered C) cannot be directly attributed to peat. A holistic view over the life cycle of afforestation should take a dynamic approach to the net carbon exchange of the forest ecosystem in question and calculations should include assessment of, for example, how the carbon stored in wood products is managed during that time (Kilpeläinen et al. 2011). For example, carbon released immediately to produce bioenergy creates instant emissions whereas carbon stored in wood products with a long lifetime is released much later. Changes in bioenergy production practices may also affect the C stocks discussed above, and any reductions in these stocks should be interpreted as indirect emissions that must be allocated accordingly in the LCA. For example, introducing the collection of forest harvest residues for energy production significantly increases C losses from the forest, depending on the quantity and nature of the residues removed and the climatic conditions affecting natural decomposition rates (Repo et al. 2010, 2011). However, our study showed that C sequestration in biomass did not ultimately have a significant impact on the final results. The contribution of emissions from the initial reference situation is more important than the amount of CO_2 sequestration by tree growth and litter accumulation in the afforestation phase when one is considering the climate impacts of peat fuel.

As a whole, in the case of FDP with afforestation as after-treatment option, the after-treatment phase accounted for

approximately 11 % of the GHG emissions from the full peat production phase, according to the best available data, when a 300-year time perspective is applied and emissions in the reference situation are not subtracted out (see Fig. 3a and b). The value for the 'CP, afforestation' case was roughly similar (8 %). For the case of 'PM, restoration', however, the value was much higher (24 %), because of the high CH_4 emissions from restored peatland. However, in this case too, the emissions in the initial reference situation are higher than those in other cases.

4.5 The temporal perspective

The calculation method used in this study is dynamic so in principle addresses the temporal variation in climate impacts throughout any calculation period. However, it is obvious that the length of this period, or the time perspective (e.g. 50, 100 or 300 years' time span) selected for the analysis, has a strong effect on the interpretation of the final results. In some cases, climate impacts have been calculated over a period as long as 300 years, which has been justified by the time scale of the IPCC's GHG concentration stabilisation scenarios (Kirkinen et al. 2008) and the slow response of GHG balances during the after-treatment phase (Kirkinen et al. 2007; Hagberg and Holmgren 2008).

There are different opinions about what constitutes an 'acceptable' time perspective in the context of climate change mitigation. It can be argued, however, that the threat of rapid climate change calls for energy production solutions with very low RF impacts in a short-term perspective of clearly under 100 years. For example, to limit the increase in the world's average temperature during the twenty-first century to less than 2 °C relative to pre-industrial levels, strict GHG emission reductions are necessary already in the next few decades (Meinshausen et al. 2009; Rogelj et al. 2011).

Even if the perspective of climate change mitigation were to be ignored, it should be noted that key input data for RF calculations—i.e. the gas exchange rates—represent today's conditions and knowledge. Understanding of atmosphere–biosphere exchange of GHGs, including responses to climate change, has advanced considerably over the last decade but is still clearly insufficient for incorporation of any century-scale variations into an LCA. Furthermore, this would require region-scale information on the development of meteorological and hydrological conditions over an extended period and scenarios for additional external factors such as forest management practices. Therefore, it is important to understand that the results of studies similar to the present one become increasingly uncertain with time, as the long-term dynamics of GHG fluxes are not considered. In practice, a perspective of over 100 years entails uncertainty so great that we do not recommend using the associated results for decision-making.

4.6 Uncertainties in peat fuel LCA

In LCA, uncertainties are commonly grouped into parameter uncertainty, scenario uncertainty and model uncertainty. In most real-life LCA applications, however, uncertainties are not assessed. This should not be the case, since it is evident that potentially great uncertainties exist (e.g. Lloyd and Ries 2007; Mattila et al. 2012).

In the discussion that follows, we mainly focus on parameter uncertainty, which can be caused by uncertainty related to emissions and other inventory data variables, and uncertainty related to various factors that are necessary if one is to obtain input or output variables or impact assessment results (e.g. emission factors). However, also scenario uncertainty (i.e. the uncertainty caused by normative choices in LCA such as selection of system boundaries) can be important. Model uncertainties, related to selection or formulation of the models used in the RF calculations, turned out to be unimportant in the present case (Seppälä et al. 2010), in which previous LCAs were compared. This is because the RF models used in these studies were based on essentially identical concepts, with the differences originating mainly from the parameter uncertainty. However, the results would be very different if the RF impact of the albedo change resulting from the change in land use were included in the model, in addition to the GHG balances. Lohila et al. (2010) showed that the decreasing albedo resulting from the forestation of boreal peatland can balance out or even exceed the cooling effect due to the changing GHG fluxes.

Estimating the climate impacts of peat fuel utilisation chains in a given time interval requires the combination of a large number of parameter estimates and models, of many types. The parameter uncertainty has two possible interpretations. First, in most cases, the 'true' values of various parameters (e.g. the CO_2 emissions of peatlands in a certain place and time) are unknown, so we are actually utilising estimates instead of real-world values. Second, the generalisation of certain parameter values obtained from specific measurements in a given time and place to be utilised for the whole country may feature large uncertainties. In addition to uncertainty, the parameter estimates can have biases, and, therefore, the estimated value can give a misleading picture of the LCA impacts.

Given the complexity of the problem under analysis, the overall impacts of parameter uncertainty could be studied by means of Monte Carlo simulation of the predictive distribution of the radiative forcing profiles as a function of time (see, for example, the work of Leskinen et al. 2009). However, the uncertainties of the overall conclusions can be estimated without comprehensive simulations as they are mainly connected to other components of the radiative forcing calculations than the direct emissions caused by the combustion process. The emissions of combustion can be measured with relatively high accuracy, while, for example, the net climate change impacts of after-treatments feature large uncertainties. Now, if it is also

taken into account that serious efforts should be undertaken against global warming over a relatively brief time period, it can be concluded that uncertainties in addition to combustion cannot change the overall picture of the peat fuel utilisation LCA results. This can be seen from Fig. 3b, where the net climate impact is mostly derived from the emissions of the combustion phase even in these scenarios calculated for a 100- and 300-year temporal perspective. Furthermore, the shorter is the time perspective in peat fuel utilisation chain LCA, the more important is the effect of the combustion phase of 20 years on the final results. On the other hand, detailed uncertainty analyses and examination of the variation of parameter values between different areas and time scales could create possibilities for improving the climate impacts of peat utilisation chains in certain specific cases.

5 Conclusions

In the LCA case studies that consider product systems with a strong relationship to land use, the variation in the yield obtained from a certain land area has a significant effect on the final impact results. In our study, the functional unit was 1 PJ of peat fuel energy, but the acreage required for this may vary case-specifically. Therefore, the climate impact is very much dependent on the local circumstances affecting peat yields. In this paper, only average values have been used. It is not clear what the actual range of the values is at different peat harvesting sites. Additionally, emission values vary significantly between different types of peatlands. The judgement as to whether a site is worth peat extraction from the standpoint of climate impacts could be made through the use of site-specific emission information—in addition to the peat yield data—if it is available. More emission measurements, however, are needed if we are to be able to assess more accurately how the emissions vary between sites. In addition to what has been said above, there is also need for better site-specific data on tree growth rates, which are used in calculation of C exchange between soil, vegetation and atmosphere.

The temporal perspective has a strong impact on results and their interpretation. The more long-term the perspective, the greater is the impact of the reference situation and the after-treatment phase on the final outcomes of the study. And in the net emissions approach, where the emissions of the initial situation are subtracted from those of the peat fuel utilisation phases, a longer time span means more emissions from the initial situation being allocated to the after-treatment phase, because peat harvesting and combustion lasts only 20 years, on average. Because climate change mitigation requires quick actions and because uncertainties related to emissions increase with the time span, it can be concluded that a time perspective over 100 years is not recommendable.

Finally, the initial reference situation must be defined very carefully. The result should represent the net impacts of the particular human activity under study. To this end, the initial reference situation should be as close to the natural conditions as possible.

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